Experimental study on uniaxial tensile and compressive behavior of high toughness cementitious composite

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ABSTRACT. Though the principle of orthogonal experimental design, the uniaxial compression experiment and uniaxial tensile experiment were carried out on nine groups of high toughness cementitious composites with different mixing ratios to study the influence of four factors, namely fly ash content, water-binder ratio, sand-binder ratio and plasticizer content on the compressive strength and ultimate tensile strain of high toughness cementitious composites. The experiment results show that PVA fibers content greatly influenced the flexural behavior and the influence of the four factors on the compressive strength and ultimate tensile strain of high toughness cementitious composite is basically the same, the primary and secondary order is: water-binder ratio, fly ash content, plasticizer content and sand-binder ratio.

KEYWORDS. High toughness cementitious composite; Orthogonal experiment design; Mixing ratio; Compressive strength; Ultimate tensile strain.

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INTRODUCTION

High toughness cementitious composite is a new type of composite material which is formed by the incorporation of monofilament staple fibers into the cement matrix and homogeneously dispersed. It is also called engineered cementitious composite (ECC), which was initially developed by Victor C. Li [1, 2]. This material can generate multiple fine cracks in the tension process. Ultimate tensile strain may reach several hundred times that of ordinary concrete, while the stress may increase when the strain increases, so it has a quasi-strain hardening property and excellent toughness [3, 4]. ECC can be used in road surface, bridge and dam maintenance as well as aseismic hardening or serves as a new important material for new structures [5]. However, at present there is no recognized ECC mix design. Besides, there are no established norms or standards proposed regarding the regularities between mixing ratios and the mechanical

properties of ECC. In concrete structures, the compression performance must be guaranteed for columns, walls and other load-bearing members. Due to the deficiency of coarse aggregate, the increase in strength of ECC will be limited to a certain extent. Therefore, in order to promote the ECC in concrete structures, it is necessary to design an appropriate mix ratio to ensure that it has reliable strength, but also good toughness.
The classic mixing ratio of ECC showed that the raw materials made up of cement, fly ash, fine quartz sand, water and monofilament staple fibers. On the one hand, an excessive water-binder ratio could severely reduce the strength of the material because it lacks coarse aggregate; on the other hand, if the water-binder ratio is too small, the fluidity of the mixture may deteriorate, which could hinder the dispersion of fibers. In this experiment, the superplasticizer was used to reduce the amount of water, while ensuring a good fluidity of the mixture. In this paper, four main factors, namely fly ash content, sand-binder ratio, water-binder ratio and plasticizer content were considered, using the compressive strength and ultimate tensile strain of ECC as indexes. The influence of the regularities of various factors on the strength and toughness of high toughness cementitious composites was studied through the orthogonal experiment.

EXPERIMENTAL DESIGN

Experimental materials

The cementitious materials consist of P.O 42.5 ordinary Portland cement and first-grade fly ash. Fine quartz sand with a size of 0.1mm-0.2mm was used as fine aggregate. Ordinary tap water with polycarboxylic superplasticizer was used to mix the dry material.
Previous studies showed that polyvinyl alcohol (PVA) and polyethylene (PE) fiber were the primary types of fiber to manufacture ECC. C. Redon adopted different amounts of special oil coated with the surface of PVA fiber, and found those which could dissipate a large amount of energy in the process of gradually pulling out from the cement matrix [6]. In this paper, Kuraray™ PVA fiber (Φ15μm×12mm) was used to manufacture high toughness cementitious composites.

Orthogonal design

The mix proportion of concrete is commonly tested with either one variable or multiple variables at a time. Each of the two methods has its unique advantages and disadvantages. The one-variable-at-a-time method is not representative enough and limited to a small range, while the multiple-variable-at-a-time method requires repeated tests on the interacting factors. For instance, in the case of three factors and three levels, 27 tests need to be carried out, making the experiment extremely complicated.
The merits of the above two methods are combined into the orthogonal test method. Based on mathematical statistics principles, the test solution relies on a set of orthogonal forms to sieve out the most representative samples for comprehensive tests, aiming to obtain the effect of factors on indices and identify the best combinations of influencing factors [7]. In the orthogonal test, the test factors refer to those influencing the object, and the levels denote the conditions of the test factors. In this research, the test factors include fly ash content, sand-binder ratio, water-binder ratio and plasticizer content, each of which has three levels of conditions. The purpose of the orthogonal test is to examine the impact of the test factors on the compressive strength and the ultimate tensile strain of materials.

Level of Factor	Fly Ash Content	Sand-binder Ratio	Water-binder Ratio	Plasticizer Content
	(A)	(B)	(C)	(D)
1	0.9	0.30	0.20	0.40%
2	1.2	0.33	0.23	0.70%
3	1.5	0.36	0.26	1.00%

Table 1: Factors and levels of orthogonal test.

Mixing ratio

This study took fiber with a volume content of 2.0% as an invariant, considered the four factors fly ash content, sand-binder ratio, water-binder ratio and plasticizer content. Each factor includes three levels,as shown in Table 1. Three-level variables of fly ash content adopted the mass ratio of fly ash to cement ($m_{FA/C}$), being equal to 0.9, 1.2 and 1.5 which were respectively expressed by A1, A2 and A3. Three-level variables of the sand-cement ratio adopted the mass ratio of sand to cementing materials ($m_{S/B}$) for the 0.30, 0.33 and 0.36 and were respectively expressed by B1, B2 and B3. Three-level variables of the water-cement ratio adopted the mass ratio of water to cementing materials ($m_{W/B}$), being equal to 0.20, 0.23 and 0.26, respectively expressed by C1, C2 and C3. After the preliminary exploratory experiment, the mass ratios of superplasticizer to cementing material were set to 0.4%, 0.7% and 1.0%, which were expressed by D1, D2 and D3 respectively.

EXPERIMENTAL PROCEDURE

Uniaxial compression experiment

The compressive strength of concrete is one of the basic mechanical properties; however, for ECC compression performance experiments, there are currently no uniform standards and norms. Victor C. Li [8] carried out the axial compression experiment with an ECC cylinder with a specimen of the size Φ75mm×150mm and compared the test results to ordinary concrete. The team of Shilang Xu [9] conducted the uniaxial compression experiment with an ECC cube that has a side length of 40 mm and a 40mm×40mm×160mm prism specimen, and measured the uniaxial compressive stress-strain curves. Chunhong Hu et al. [10] used a 40mm×40mm×160mm prism of ECC specimens to study the strength under uniaxial compression and found the rule that the peak strain and ultimate compressive strain were both significantly larger than that of ordinary concrete. Mingke Deng et al. [11]used ECC cubes with side lengths of 100mm and 70.7mm to carry out the uniaxial compression experiment, then found the secondary compressive strength of the ECC was close to the first compressive strength, which shows that the resistance to damage of ECC is obviously better than that of ordinary concrete. In this paper, the uniaxial compression experiment on an ECC cube with the size of 100mm×100mm×100mm was carried out.

The fibers were mixed last when producing ECC; that is, the cement, fly ash and sand were first put into the blender and mixed for 1 to 2min, then the water and superplasticizer were added and mixed for 4 to 5min, fibers were slowly added and finally mixed 8 to 10min until the it were dispersed evenly. The specimens should undergo vibrating compaction after ECC is poured into the mold, then released after standing 36 hours and put into the standard curing box for curing. The orthogonal experiment includes nine groups' mixing ratios. The uniaxial compression experiment was carried out on each specimen in accordance with relevant provisions of GB/T 50081-2002 Ordinary Concrete Mechanical Performance Test Method Standards [12].

Experimental phenomena and results

During the experiment, it was found that the compression failure process of high toughness cementitious composite was obviously different from ordinary concrete. During the loading process, the vertical micro cracks first appeared in the central part of the specimen. As the load continued to increase, the cracks developed obliquely toward the end of the specimen and new fine cracks were formed near the original crack zone. When the load was applied close to the ultimate load, the crack developed rapidly and the width of the crack began to increase; simultaneously, the lateral deformation of the specimen increased gradually and the sound of fiber breaking and pulling out of the specimen could be heard. Finally, part of the cracks across the entire section and the bearing capacity began to decline, which indicated specimen failure. All the specimens in the experiment did not show the phenomenon of bursting apart and peeling similar to ordinary concrete, but after unloading, the specimens were found to have undergone obvious compression deformation, but to maintain good integrity. The experimental data of each group mixing ratio were obtained and reported in Table 2.

Orthogonal analysis

Taking factor (A fly ash content) as an example, below is a simple illustration of how the range of a factor is determined. If we denote the total compressive strength of factor A at each of the three levels as K_1, K_2 and K_3, respectively, and the average compressive strength at each of the three levels as $\bar{K}_1$, $\bar{K}_2$ and $\bar{K}_3$, respectively, then we have:

$$K_1 = 55.3+47.4+39.9=142.6, \text{(Z1, Z2, Z3 test group)} \quad (1)$$

$$K_2 = 47.3+38.5+61.4=147.2, \text{(Z3, Z4, Z5 test group)} \quad (2)$$

$$K_3 = 37.9+55.4+43.3=136.6, \text{(Z6, Z7, Z8 test group)} \quad (3)$$

$$\bar{K}_1=K_1/3=142.6/3=47.5 \quad (4)$$

$\bar{K}_2 = K_2/3 = 147.2/3 = 49.0$ (5)

$\bar{K}_3 = K_3/3 = 136.6/3 = 45.5$ (6)

The size of the range R is introduced to measure the impact of factors on the test indices. The importance of a factor is positively correlated with the size of its range. If a factor has a big range, any variation in the level of the factor will significantly affect the test indices, and the inverse is true. The size of the range R is calculated as follows:

$R = (\bar{K}_i)_{max} - (\bar{K}_j)_{min} = 49.0 - 45.5 = 3.5$ (7)

The range of other factors is calculated in the same way. The results are listed in Table 2.

Test Group	A Fly Ash Content	B Sand-binder Ratio	C Water-binder Ratio	D Plasticizer Content	Compressive Strength (MPa)
Z1	1(0.9)	1(0.30)	1(0.20)	1(0.40%)	55.3
Z2	1(0.9)	2(0.33)	2(0.23)	2(0.70%)	47.4
Z3	1(0.9)	3(0.36)	3(0.26)	3(1.00%)	39.9
Z4	2(1.2)	1(0.30)	2(0.23)	3(1.00%)	47.3
Z5	2(1.2)	2(0.33)	3(0.26)	1(0.40%)	38.5
Z6	2(1.2)	3(0.36)	1(0.20)	2(0.70%)	61.4
Z7	3(1.5)	1(0.30)	3(0.26)	2(0.70%)	37.9
Z8	3(1.5)	2(0.33)	1(0.20)	3(1.00%)	55.4
Z9	3(1.5)	3(0.36)	2(0.23)	1(0.40%)	43.3
K_1	142.6	140.5	172.1	137.1	
K_2	147.2	141.3	138.0	146.7	
K_3	136.6	144.6	116.3	142.6	
$\bar{K}_1$	47.5	46.8	57.3	45.7	
$\bar{K}_2$	49.0	47.1	46.0	48.9	
$\bar{K}_3$	45.5	48.2	38.7	47.5	
R	3.5	1.4	18.6	3.2	

Table 2: Orthogonal experiment result of compressive property.

As can be seen in Table 2, for the four factors considered in the experiment, the range in decreasing order is: water-binder ratio, fly ash content, plasticizer content and sand-binder ratio. The range of the water-binder ratio is 18.6, which is far greater than the range of the other three factors. This result indicates that the water-binder ratio has the greatest influence on the compressive strength of ECC, followed by fly ash content, plasticizer content and sand-binder ratio.

In order to further analyze the impact of each factor on the compressive strength, a relationship curve diagram was drawn, taking the change of each factor as an abscissa and the average compressive strength $\bar{K}_i$ as an ordinate. According to the results of the range analysis and Figure 2:

1) The water-binder ratio is the key factor in the compressive strength of high toughness cementitious composites, and the strength increases with the decrease of the water-binder ratio. If the water-binder ratio is too large, the internal porosity of the material will increase, which can directly lead to lower compressive strength.

2) In the experiment, the mass ratio of fly ash to cement is in the range of 0.9 - 1.5. The compressive strength increases first and decreases later with increasing fly ash content. Fly ash is made up of a large number of subtle spherical vitreous compositions with fine particle size, which can play a role in improving the mobility of the mixture. Meanwhile, there is the Pozzolanic Effect of fly ash, namely the chemical reaction of fly ash and cement hydrate. The products of the chemical reaction are often filled in the pores of the cement hydrate, reducing the interior porosity of the mixture and improving the compactness of the material. However, the active effect of fly ash should lag behind the hydration reaction

of cement, which may cause a negative influence on the density and strength of the materials in the early stage of hydration [13].

3) The addition of superplasticizer can disperse and lubricate the cement, which reduces the water consumption and makes the uniformity of the mixture better. However, if the plasticizer content is too large, it may extend the setting time of the high toughness cementitious composite and reduce its initial strength. In this experiment, the compressive strength first increases and then decreases with the mass ratio of superplasticizer to cementing material changing from 0.4% to 1.0%, indicating there is an optimum dosage of superplasticizer.

4) Experimental data indicate that the compressive strength increases by 0.6% and 3.0% with the sand-binder ratio changing from 0.30 to 0.33 and 0.36. According to the result of the range analysis, the impact of sand-binder on the compressive strength of the material is minimal.

Figure 1: Failure mode of test specimens.

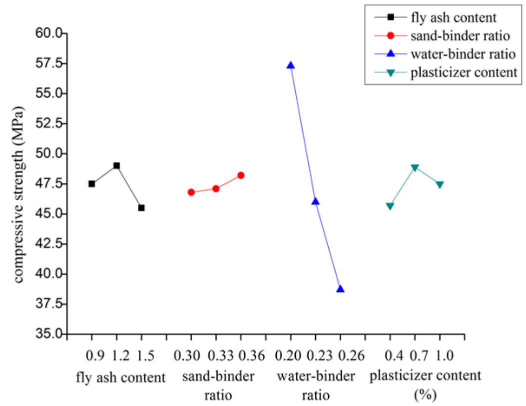


Figure 2: Influence of Changes in Factors on Compressive Strength.

UNIAXIAL TENSILE EXPERIMENT

Literature [14] found through a large number of experiments that cracks could be extended to steady-state cracking mode during the tensile experiment of the high toughness cementitious composite. The tensile stress instantly dropped when the first crack appeared and then immediately returned, then new cracks were created as the load increased without increasing the crack width. Jun Zhang et al. [15] carried out the tensile experiment with ECC prism specimens using six different mixing ratios. The tensile stress-strain curve was measured and the ultimate tensile strain was found to be 1.7%. Shilang Xu [16] used thin plate specimens of ECC to carry out the tensile experiment. The result showed that ECC had a significant quasi-strain hardening property and the crack width could be effectively controlled within 100 μm.

Figure 3: The thin Plate Specimen for uniaxial compression experiment.

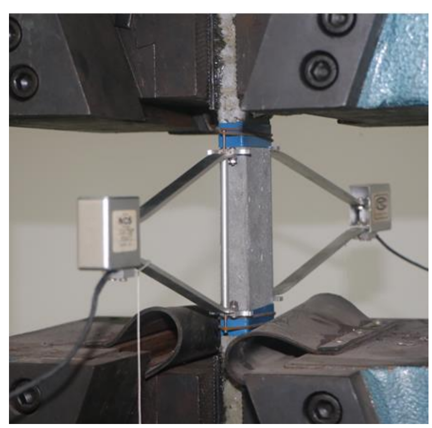


Figure 4: Experimental set-up for niaxial tensile test.

In this paper, the uniaxial tensile experiment on an ECC thin plate specimen of the size 300mm×50mm×15mm was carried out. Steel sheets with a thickness of 1 mm were affixed to both ends of the specimen to prevent partial damage to the holding parts of the specimen, as shown in Figure 3.
The experiment was carried out on a 1000kN microcomputer-controlled servo-hydraulic testing machine and the load was applied in the displacement control mode at a speed of 0.0025 mm/s. Meanwhile, the strain data were collected on both sides of the specimen with extensometers. The test apparatus is shown in Figure 4.

Experimental phenomena and results

The results showed that the failure process of all specimens could be divided into three stages: elastic stage, multiple crack development stage and failure stage. During the loading process, the first crack was found to have appeared in the weak section, and then there were many fine cracks that appeared immediately around it. All specimens exhibited quasi-strain hardening behaviour, and the ultimate tensile strain of ECC was much larger than that of ordinary concrete. The experimental results of the nine groups of different mixing ratios are shown in Figure 5.

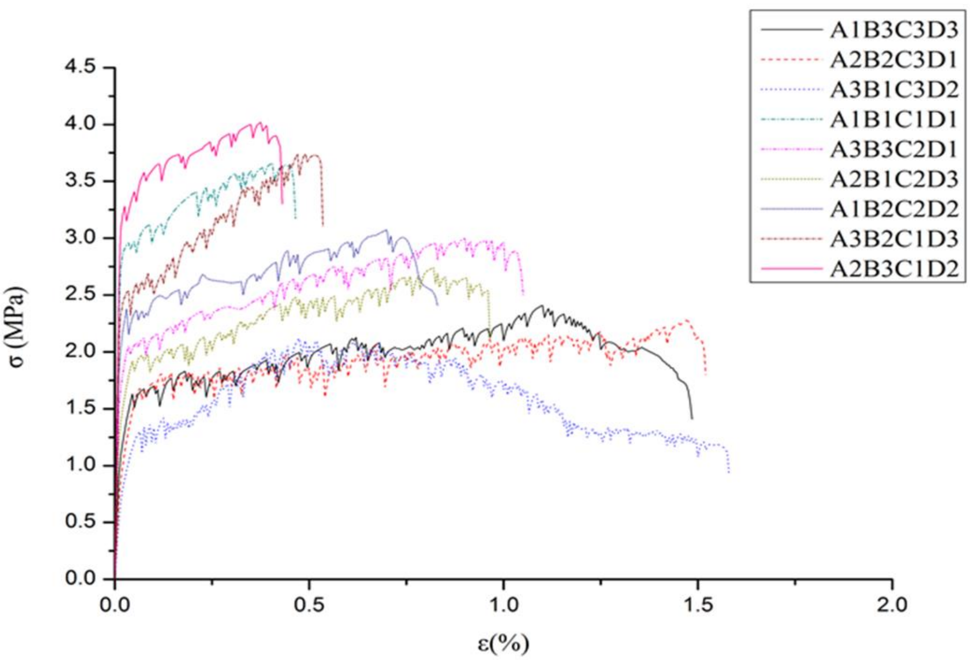


Figure 5: Tensile Stress - strain Curve of 9 experimental groups.

Orthogonal analysis

It's similar to the range calculation method of factor A in terms of compressive strength so it's not repeated hereby. Calculation results are shown in Table 3. As can be seen in Table 3, the range decreasing order is: water-binder ratio, fly ash content, plasticizer content and sand-binder ratio, and the range of water-binder ratio is 1.051, which is far greater than the range of the other three factors. This indicates that the water-binder ratio has the greatest influence on the ultimate tensile strain of ECC, followed by fly ash content, plasticizer content and sand-binder ratio.
The relationship curve diagram shows the change of each factor as an abscissa and the average ultimate tensile strain as an ordinate.
Based on the results:
1) The water-binder ratio is the key factor that affects the ultimate tensile strain of high toughness cementitious composite, and the greater the water-binder ratio is, the higher the ultimate tensile strain is, meaning the better the toughness is.
2) The ultimate tensile strain increases with the increase of fly ash content. The chemical reaction of fly ash with cement hydrate can improve the properties of the interface between fibers and matrix; moreover, there are a large number of fly ash spherical particles attached at the surface of the fibers, reducing the adhesion between fiber and matrix and having a positive impact on the realization of the strain-hardening.
3) The experimental results show that the sand-binder ratio and plasticizer content have little effect on the ultimate tensile strain.

Test Group	A Fly Ash Content	B Sand-binder Ratio	C Water-binder Ratio	D Plasticizer Content	Ultimate Tensile Strain (%)
Z1	1(0.9)	1(0.30)	1(0.20)	1(0.40%)	0.458
Z2	1(0.9)	2(0.33)	2(0.23)	2(0.70%)	0.825
Z3	1(0.9)	3(0.36)	3(0.26)	3(1.00%)	1.482
Z4	2(1.2)	1(0.30)	2(0.23)	3(1.00%)	0.96
Z5	2(1.2)	2(0.33)	3(0.26)	1(0.40%)	1.51
Z6	2(1.2)	3(0.36)	1(0.20)	2(0.70%)	0.424
Z7	3(1.5)	1(0.30)	3(0.26)	2(0.70%)	1.575
Z8	3(1.5)	2(0.33)	1(0.20)	3(1.00%)	0.532
Z9	3(1.5)	3(0.36)	2(0.23)	1(0.40%)	1.045
K_1	2.765	2.993	1.414	3.013	
K_2	2.894	2.867	2.830	2.824	
K_3	3.152	2.951	4.567	2.974	
$\bar{K}_1$	0.922	0.998	0.471	1.004	
$\bar{K}_2$	0.965	0.956	0.943	0.941	
$\bar{K}_3$	1.051	0.984	1.522	0.991	
R	0.129	0.042	1.051	0.063	

Table 3: Orthogonal Experiment Result of Tensile Property.

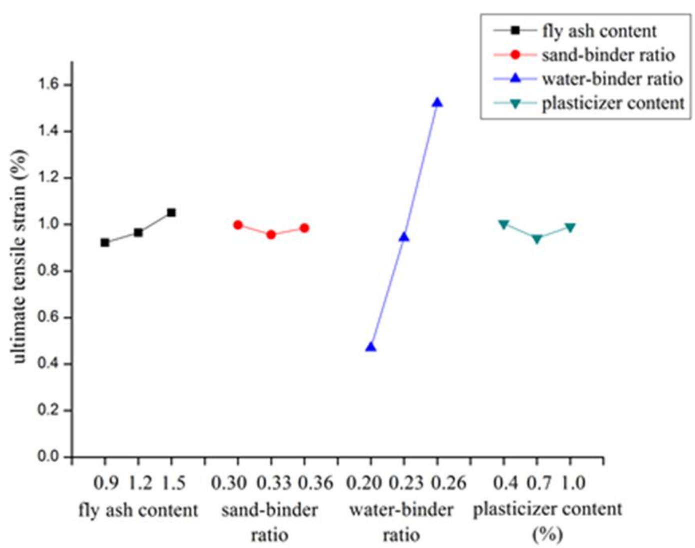


Figure 6: Influence of Changes in Factors on ultimate tensile strain.

DISCUSSION ABOUT THE TOUGHENING MECHANISM OF PVA FIBERS

In general, the numerous initial microdefects in the concrete matrix were demonstrated as tiny cracks in the loading process. According to the test, it is concluded that fibers should take up 2% of the volume of the specimen and should be randomly distributed throughout the specimen. Capable of bridging the initial microdefects, plenty of fibers can obviously reduce the occurrence and expansion of tiny cracks. As much of the matrix is held together by fibers, it is less likely for microdefects to develop in the initial phase. Thanks to the fibers, the specimen is fortified on the inside, making the matrix more resistant to deformation [17].

Figure 7 displays the form of the specimen at the peak load and after the failure. No burst fracture is observed in the test. At the peak load, the multiple tiny vertical cracks on the specimen gradually developed into major connected cracks; the crack development is accompanied by the sound of fibers being strained or broken. Whereas the fibers hold the matrix together and the material has the strain-hardening property, the stress state of the ECC in uniaxial loading is similar to that of the confined concrete under conventional triaxial loading. In this test, the specimen exhibited the squeezing flow failure similar to that of confined concrete [18].
When macroscopic cracks begin forming (Fig.8, a), fibers between the crack sections are interlaced and evenly distributed. Fibers at the crack parts bear the majority of the tensile force, which prevents further development of cracks. The cracks at this stage are mainly the outcome of the bridging role of fibers. In other words, on the crack surface, the concrete matrix delivers the stress to fibers which rely the surface to convey the stress to the concrete matrix around that doesn't have cracks. When the cracking strength of the matrix around reaches the limit, new cracks will appear, which is reflected in increasing cracks on specimens. Strain hardening is realized through formation of multiple cracks. The process will last until the surface fibers are collectively pulled out or broken. Specimens show remarkable extensibility [19]. Fig. 8(b) displays the failure mode of specimens in the direct tensile test. It can be noted that a number of cracks show up on the specimen surface, which indicates that desirable adhesive performance exists between PVA fibers and the matrix. It prevents further expansion of tiny cracks. With such strain hardening behavior, the strength and toughness of materials are significantly enhanced [20].

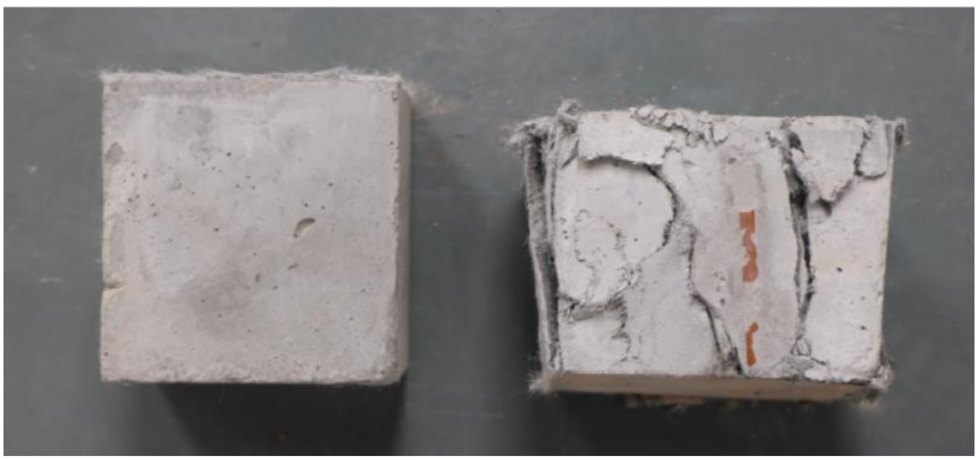
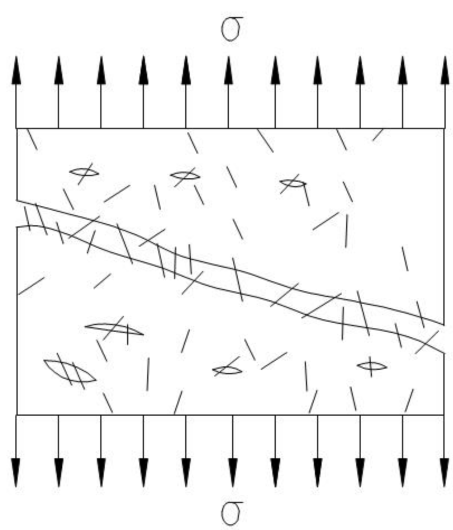
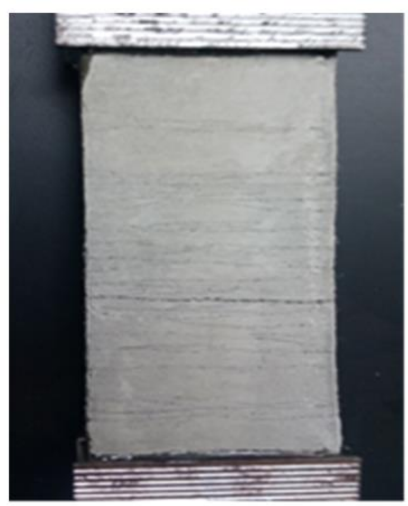


Figure 7: Failure mode comparison of ECC cube specimens in different phases of loading.



(a)



(b)

Figure 8: (a) Micro-crack bridging and ductility enhancement effect of PVA fibers; (b) Typical multiple cracks on ECC thin plate specimen under tensile load.

Conclusion

In this paper, the orthogonal experiment was carried out to study the compressive property and tensile property of high toughness cementitious composite, and the preliminary conclusions are as follows:
1) The failure pattern of high toughness cementitious composite is significantly different from ordinary concrete. There is no phenomenon of sudden collapse when it is damaged by compression, and all the specimens can maintain a good integrity without the phenomenon of peeling. There are a large number of fine cracks that appeared in almost the entire area of the specimen during the process of tension, showing the characteristic of significant quasi-strain hardening. Finally, it is proved that the ultimate tensile strain of high toughness cementitious composites is much larger than that of ordinary concrete.
2) No matter whether for compressive strength or ultimate tensile strain, the primary and secondary order of the influence of the four factors is: water-binder ratio, fly ash content, plasticizer content and sand-binder ratio. In terms of compressive strength, the smaller the water-binder ratio, the higher the strength; and the compressive strength increases first and then decreases with the addition of fly ash or plasticizer content. However, the effect of sand-binder ratio on the compressive strength is relatively small. For the toughness of the material, the ultimate tensile strain improves with the increase of the water-binder ratio or fly ash content; the influence of sand-binder ratio and plasticizer content is not obvious.
3) Considering both compressive strength and toughness, the water-binder ratio is the key factor, because the influence of it on both is far greater than that of other factors. Yet it should be noted that the influence of water-binder ratio on compressive strength and toughness is diametrically opposed. Taking into account the main feature of ECC, namely its superior toughness, the water-binder ratio should be increased as much as possible while ensuring the compressive strength will not be too low.

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References

[1] Zhang, J., Li., V. C., Effect of inclination angle on fiber rupture load in fiber reinforced cementitious composites, Composites Science & Technology, 62 (2002) 775–781.
[2] Li, V. C., Large volume, High-performance applications of fibers in civil engineering, Journal of Applied Polymer Science, 83 (2010) 660-686.
[3] Li, V. C., Leung, C. K. Y., Theory of steady state and multiple cracking of random discontinuous fiber reinforced brittle matrix composites, ASCE Journal of Engineering Mechanics, 118 (1992) 2246—2264.
[4] Wang, S., Li, V. C., Engineered cementitious composites with high-volume fly ash, Aci Materials Journal, 104 (2007) 233-241.
[5] Mirandola, A., Lorenzini, E., Energy, environment and climate: from the past to the future, International Journal of Heat and Technology, 34 (2016) 159-164.
[6] Redon, C., Li, V. C., Wu, C., et al. Measuring and modifying interface properties of PVA fibers in ECC matrix, Journal of Materials in Civil Engineering, 13 (2001) 399-406.
[7] Chi, Y., Xu, L., Zhang, Y., Experimental study on hybrid fiber–reinforced concrete subjected to uniaxial compression, Journal of Materials in Civil Engineering, 26 (2014) 211-218.
[8] Li, V. C., Mishra, D. K., Wu, H. C., Matrix design for pseudo strain-hardening fiber reinforced cementitious composites, Material and Structures, 28 (1995) 586-L595.
[9] Xu, S. L., Cai, X. R., Zhang, Y. H., Uniaxial compressive stress-strain full curves and measurement of ultrahigh toughness fiber reinforced cement matrix composites, China Civil Engineering Journal, 42 (2009) 79-85.
[10] Hu, C. H., Gao, Y. E., Ding, W. C., Experimental on compression properties of ultrahigh toughness cementitious composite properties, Journal of Building Structures, 34 (2013) 128-132.

[11] Deng, M. K., Qin, M., Liang, X. W., Experimental research on high ductile fiber reinforced concrete compressive properties, Industrial Construction, 45 (2015) 120-126.
[12] GB/T 50081-2002 Ordinary Mechanical Properties of Concrete Test Method Standards, Beijing: China Building Industry Press, (2003).
[13] Zhang, H.Y., Thermodynamic property of concrete and temperature field analysis of the base plate of intake tower during construction period, International Journal of Heat and Technology, 33 (12015) 145-154.
[14] Li, V. C., Wang, S., Wu, C., Tensile strain-hardening behavior of polyvinyl alcohol engineered cementitious composite (PVA-ECC), ACI Materials Journal, 98 (2001) 483-492.
[15] Gong, C. X., Zhang, J., Tensile performance of high ductile fiber reinforced cementitious composite, Journal of Hydraulic Engineering, 39 (2008) 361-366.
[16] Xu, S. L., Li, H. D., Uniaxial tensile experiments of ultra high toughness cementitious composite, China Civil Engineering Journal, 42 (2009) 32-41.
[17] Spagnoli, A., A micromechanical lattice model to describe the fracture behaviour of engineered cementitious composites, Computational Materials Science, 46 (2009) 7-14.
[18] Kabele, P., Multiscale framework for modeling of fracture in high performance fiber reinforced cementitious composites, Engineering Fracture Mechanics, 74 (2007) 194-209.
[19] Li, V. C., Wang, S., Microstructure variability and macroscopic composite properties of high performance fiber reinforced cementitious composites, Probabilistic Engineering Mechanics, 21 (2006) 201-206.
[20] Yang, E. H., Yang, Y. Z., Li, V. C., Use of high volumes of fly ash to improve ECC mechanical properties and material greenness, Aci Materials Journal, 104 (2007) 620-628.